Development of GaN Vertical Trench-MOSFET with MBE Regrown Channel

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Primary CNF Tools Used: PT770 etcher, Autostep 200, Oxford PECVD, Oxford 81 etcher, Heidelberg mask writer DWL2000, SC4500 odd-hour evaporator, AJA sputter deposition, Oxford ALD FlexAL, DISCO dicing saw, Veeco Icon AFM

Abstract:

GaN vertical trench-MOSFETs incorporating molecular beam epitaxy (MBE) regrown channel are developed and investigated. The channel regrowth by MBE prevents repassivation of the *p*-type GaN body while promising higher channel mobility. A respectable 600 V breakdown voltage (BV) is measured in the absence of edge termination, indicating a decent critical field strength (> 1.6 MV/cm) of the regrown channel. However, the on-resistance is limited by the highly resistive lateral channel due to Mg incorporation. With an additional n^+ buried layer, excellent on-current of 130 mA/mm and on-resistivity of 6.4 m$\Omega \cdot cm^2$ are demonstrated, but the BV is limited by high source–drain leakage current from the channel due to drain-induced barrier lowering (DIBL) effect due to the presence of interface charge (~ 6Å ~ 10^{12} cm^{-2}) at the regrowth interface on etched sidewalls. This study provides valuable insights into the design of GaN vertical trench-MOSFET with a regrown channel, where simultaneous achievement of low on-resistivity and high BV is expected in devices with reduced interface charge density and improved channel design to eliminate DIBL.

Summary of Research:

GaN vertical power transistors have gained increasing interests in recent years due to the advantages over lateral transistors in high voltage/high current applications. Recently, a novel design based on trench metal oxide semiconductor field effect transistor (MOSFET) is realized by metal-organic chemical vapour deposition (MOCVD) regrowth of a thin GaN interlayer, which helps increase the channel mobility. Similar to the other MOCVD regrown devices, the buried Mg-doped *p*-GaN needs to be re-activated by exposing the *p*-GaN surface during high temperature anneal. This leads to high thermal budget and poses limitations on device geometry. Furthermore, any incomplete activation of buried *p*-GaN leads to reduced BV. In this report, we design a V-shaped trench MOSFET with molecular beam epitaxy (MBE) regrown unintentionally-doped (UID) GaN channel. Approximately 600 V breakdown voltage with normally-off operation is demonstrated without the need for re-activation of the buried *p*-GaN. To our knowledge, this is the highest BV achieved in GaN vertical transistors with MBE regrown channel.

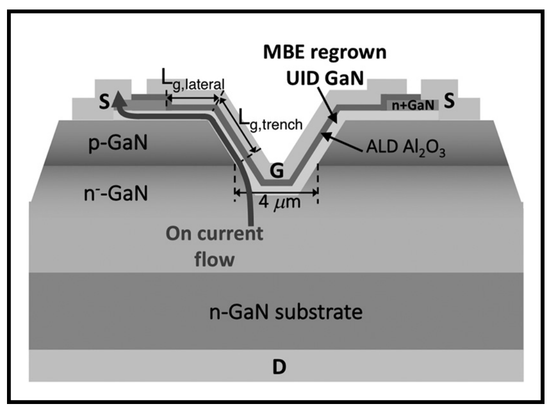


Figure 1: Schematic device structure of the GaN V-trench MOSFET.

The starting epitaxial structure is a high voltage *p-n* diodes structure grown by MOCVD. The schematic of the device is shown in Figure 1, which consists of a MBE regrown UID GaN channel covering the sidewall of the V-shaped trench. The conformal gate

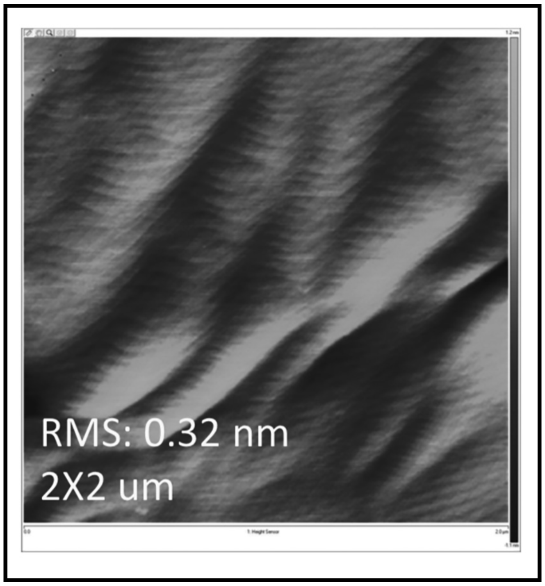
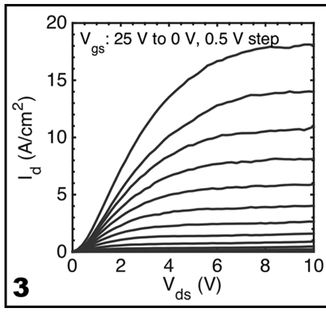


Figure 2: AFM surface morphology of the MBE regrown GaN at the trench bottom.



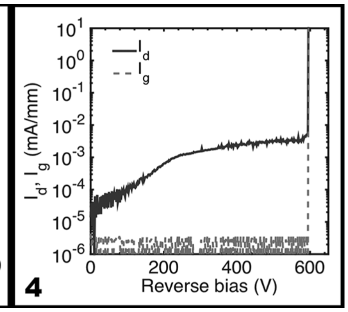


Figure 3, left: *Representative I_d-V_{ds} characteristics of a Ga_2O_3 vertical power MISFET.* ***Figure 4, right:*** *Representative three-terminal off-state (at V_{gs} = -15 V) I_d/I_g-V_{ds} characteristics and breakdown voltage of Ga_2O_3 vertical power MISFETs.*

ensures field-control of the regrown channel as well as the possible charge typically present at the regrowth interface. Smooth surface morphology of the regrown GaN at the trench bottom is observed by atomic force microscope (AFM) with clear atomic steps (Figure 2). The fabrication steps are as follows. A tapered trench is etched using our low damage Cl-based recipe on PT770 etcher with PECVD SiO_2 as mask. In order to reduce impurity concentration at the etched surface, a combination of UV-ozone cleaning and HF+HCl wet etch is performed before loading into the MBE chamber, where 50 nm UID GaN is regrown. A patterned n^+-GaN regrowth is then performed for ohmic contact purpose. Since MBE chamber has no hydrogen-containing reactants, the buried *p*-GaN remains activated. The 30 nm Al_2O_3 gate dielectric is deposited by Oxford ALD system.

The transfer curve of a single finger device shows an on-off ratio of 10^9 and normally-off operation with a threshold voltage of ~ 16 V. The output characteristics in Figure 3 show good saturation behavior and an oncurrent of ~ 18 A/cm^2 (normalized by the trench area) at V_{gs} = 25 V. R_{on} is determined from the linear region to be 0.3 $\Omega \cdot cm^2$. The relatively poor R_{on} and I_{on} is due to Mg diffusion in the lateral part of the channel from the *p*-GaN underneath. A thin n^+-GaN counter layer before the channel regrowth improves the channel conductivity dramatically [1]. The off-state characteristics in shown in Figure 4. Low drain leakage and a breakdown voltage of 596 V is measured with V_{gs} = −15 V, indicating good quality of the regrowth *p-n* junction interface.

In summary, record high 600 V BV is achieved among GaN vertical transistors with MBE regrown channel. No additional activation annealing of the buried *p*-GaN is needed, allowing for lower thermal budget and more flexible device geometry than MOCVD regrowth.

References:

[1] W. Li, K. Nomoto, K. Lee, S. M. Islam, Z. Hu, M. Zhu, X. Gao, M. Pilla, D. Jena, and H. G. Xing, IEEE Transactions on Electron Devices 65, 2558 (2018).

[2] W. Li, K. Nomoto, K. Lee, S. M. Islam, Z. Hu, M. Zhu, X. Gao, M. Pilla, D. Jena, and H. G. Xing, in Proc. 75th Annu. Device Res. Conf. (DRC) (2017), p. 1.